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CEBAF-TH-90-08

QUARK EXCHANGE FORCES from a HEAVY QUARK PERSPECTIVE*

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ABSTRACT

The exchange of quarks between hadrons can be the origin of important interhadronic forces *distinct* from those which arise in meson exchange theories. I show this to be the case in a world of heavy quarks, and discuss some implications of this observation for our understanding of the nucleon-nucleon force.

Preamble

The discussion of the importance of quark exchange forces in hadronic interactions is clouded by our inability to solve QCD at low energy. Not only is their importance relative to meson exchange forces at issue, but even their independent existence: some would argue that quark exchange forces are in general contained in a meson exchange picture. We accordingly begin our discussion of this subject by reviewing quark exchange in light quark systems using the language of a string or flux tube model. In the following section we will see how considering a world made of heavy quarks resolves much of the confusion surrounding the nature and potential importance of such forces.

Introduction (with Strings Attached)

I would like to begin this discussion of quark exchange forces in the light quark world with a bit of over-simplified and prejudicially chosen history. I have a dual purpose in doing so: one is to show you that the idea of quark exchange forces is a very old one with a fine pedigree; the other is to introduce you to the string (or flux-tube) model for hadrons.

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In the beginning there was the pion, and nucleon-nucleon forces were considered to arise from its exchange. When only a few additional mesons were known, they could simply be added coherently as contributors to the forces, but as it became clear (through the discovery of the linearly-rising Regge trajectories) that one must consider interhadron forces as arising from an infinite tower of exchanges, more satisfactory descriptions were sought. First there was the Regge theory itself, then, as the result of efforts to make this theory dual[1] *, crossing symmetric, and analytic, the Veneziano formula[2]. This formula, which was at first quite mysterious, was soon interpreted[3] as containing the dynamics of quarks connected by strings, and the string theory of hadrons was born[4]. It was eventually abandoned as a *fundamental* theory of hadrons, but it has been revived, as you all know, as a fundamental theory of everything. I want to remind you that as an *effective* theory of hadrons the string theory had many virtues. I will also explain how this effective theory may be related to QCD and argue that in either guise (an effective string theory or the QCD flux tube model[5]) it leads to quark exchange forces in addition to (and distinct from) meson exchange forces.

The string theory certainly seems to correspond very well with all of the qualitative features observed in the hadronic world: the confined quark hadronic spectrum, Regge phenomenology for cross sections, duality, etc. It was of course designed with these phenomena in mind. What is perhaps more impressive is that it also contains, at least qualitatively, many other features expected in QCD but not yet observed. To me the two most startling such examples are its predictions of hybrid mesons and glueballs. The old string theory had in addition to the known Regge trajectories others called "daughter trajectories". Some of these corresponded to states in which the string degrees of freedom were excited, in remarkably close correspondence to the flux tube model for hybrids[5]. Glueballs were required in the old string theory for consistency. Hadronic reactions were assumed to proceed by an elementary string vertex in which a string breaks, forming a $q\bar{q}$ pair, or by the time-reversed healing process. If the healing process occurs between the q and $\bar{q}$ of an ordinary meson, a closed loop of string is formed[6]. Such states can be associated with what we would today call glueballs

* Duality is the idea that a given amplitude can be viewed as arising either from t-channel exchanges *or* s-channel resonances. It is most simply visualized in terms of quark line diagrams: see below.

and indeed correspond to the glueloops of the flux tube model[5].

The exact relationship between QCD and string theory is not yet clear. There have been several attempts to make a rigorous connection[7]. Perhaps because it is the only one I understand, I prefer the pedestrian picture advocated in Ref. 5: QCD can be formulated as a theory of color electric flux lines interacting with quarks and with each other. The full QCD theory differs from the old string theory in that, for a given quark sector like $q\bar{q}$, there are an infinite number of flux line topologies which can "string" the quarks together (instead of just one) and a corresponding infinity of vertices which convert a given quark and flux line configuration into another one (instead of just one basic vertex). However, it is plausible that at long wavelengths the simple string configurations and conversions between them are dominant; this is the essence of the flux tube model.

Figure 1:

(a)the classic duality diagram for meson-meson scattering

(b)a duality diagram with a twist containing quark exchange

Quark Exchange in the String Model

We now look at quark exchange in the quark line (duality) diagrams appropriate to the string theory. Figure 1(a) shows the classic duality diagram for meson-meson scattering. The diagram should be "read" by imagining a string stretched between the quark-antiquark pairs which sweeps out a membrane in space-time. As with a Feynman diagram, all possible time orderings of space-time events are implied. If one cuts this diagram vertically after the initial vertex one exposes a $q\bar{q}$ state in the t-channel; it can have any allowed quantum numbers so that this one diagram corresponds to the exchange of a whole tower of mesons with precise relationships between their masses and coupling constants. On the other hand, a horizontal cut reveals a tower of $q\bar{q}$ meson resonances being formed in the s-channel. The physics is dual: it could be described in terms of *either* t-channel exchanges or s-channel resonances. (Note that it would be *incorrect* to sum both types of processes in this theory: a phenomenological model treating the mesons as the low-energy degrees of freedom coupled to each other in an effective Lagrangian would therefore in general give an incorrect representation of the scattering amplitudes.)

Now consider Figure 1(b). Its analog is the diagram relevant to nucleon-nucleon scattering. There are certainly time-ordered parts of this diagram, where one of the exchanged quark lines zigs backward in time before zagging forward again, which correspond to meson exchange. However, there are also time orderings where there is never an additional $q\bar{q}$ pair (this is the case for the diagram as drawn): these are quark exchange and not meson exchange diagrams. If you visualize what is happening to the string in these diagrams, you will see that the strings (not the quarks) have touched, "broken", and rejoined with a piece of the other string. A concrete picture for such processes will be discussed below in the context of the flux tube model; for now we simply note that the string picture expects them to exist.

That constituent interchange can generate important forces between composite systems is of course not a novel observation. Indeed, we are all aware of a system where such exchange forces are clearly dominant over meson exchange: the interaction between two hydrogen atoms has contributions from both electron exchange and positronium "meson" exchange. The dominance of electron exchange in atomic physics is due to both the suppression of positronium exchange by powers of α and its extremely short range. In hadronic physics neither factor particularly favors one type of force over the other (except for the pion's range) and we may expect them to be of comparable importance.

Quark Exchange in the Flux Tube Model

I have discussed quark exchange in the flux tube model elsewhere[8]; here I just want to recall the mechanism of quark exchange in that model as a specific example of a possible string dynamics underlying Fig. 1(b). Figure 2(a) shows two flux tube "topologies" associated with the $qq\bar{q}\bar{q}$ system underlying meson-

meson scattering; Figure 2(b) shows "topological mixing" between them. The pictures are "kinky" because they are drawn on a space lattice (where the flux tube model has its origin as an approximation to strong coupling Hamiltonian lattice QCD). Each of the four pictures shown (with color-electric flux lines frozen in place) is an eigenstate of the Hamiltonian in the extreme strong coupling limit. These extreme strong-coupling electric base states are perturbed for any finite lattice spacing by magnetic fluctuations which can create and destroy electric flux loops on each elementary square of the lattice. These allow the flux tube to "vibrate", but more important for our immediate focus is that they also change flux tube topology. When inserted in the elementary square where the flux tubes on the left of Fig. 2(b) almost touch, they can annihilate the two horizontal flux links on that square and create two vertical flux links. This converts the flux tube topology to that shown on the right side of the figure. Thus the processes depicted in Fig. 1(b) really happen in QCD.

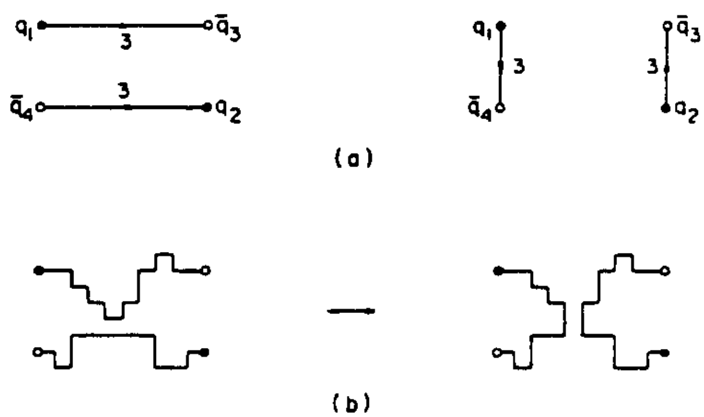

Figure 2:

(a) two low-lying $qq\bar{q}\bar{q}$ configurations

(b) topological mixing between these two configurations.

While this example shows that quark exchange is well-founded in QCD, it also shows that studying it requires that we understand gluon dynamics. For the moment, this means that calculations of quark exchange contributions to hadron-hadron scattering must be based on models. Since nonperturbative gluon dynamics is very poorly understood, there is a very large uncertainty inherent in the conclusions presently drawn on the characteristics of quark exchange forces[8].

In addition to this uncertainty is the confusion mentioned earlier over whether quark exchange is in any event a physically distinct mechanism absent from conventional meson exchange models. In the next section we will see that considering hadron-hadron scattering in a heavy quark world resolves many of the problems associated with the discussion of quark exchange. In this limit gluon dynamics *is* understood so that hadron scattering amplitudes can be calculated exactly. These calculations reveal explicitly the role of quark and meson exchange in the scattering process, showing that they are not only distinct but that quark exchange forces are completely dominant in the extreme heavy quark limit.

Quark Exchange in a Heavy Quark World

I believe that many of the issues of principle associated with quark exchange forces can be settled by thinking about a world of heavy quarks[9]. To maintain flavor parallels with our world, we consider a world with two heavy quarks U and D analogous to u and d but with $m_U = m_D \equiv m_Q \gg \Lambda_{QCD}$. The low-lying mesons and baryons of such a world will live (almost entirely) in the one-gluon-exchange region as nonrelativistic, nearly hydrogenic bound states with radii $r \sim (m_Q \alpha_s)^{-1}$.

The conventional picture of "proton"-"proton" scattering in such a world would be based on the exchange of mesons between two UUD ground states. The underpinning of such a picture is dispersion theory which tells us that the scattering amplitude should be an analytic function of momentum transfer q^2 apart from poles and cuts *determined by the physical spectrum.* We will see by examining the heavy quark limit that this statement is not accurate, and that in fact in the heavy quark limit it is completely misleading.

A Simpler Problem First

We begin by considering the simpler problem of the elastic form factor of the "proton". The usual argument is that this form factor is an analytic function of q^2 apart from vector meson poles and multiparticle threshold cuts along the real q^2 axis. Since the lowest vector meson will have a mass of approximately $2m_Q$ and since the lowest meson-meson cut will start at about $4m_Q$, one would expect on the basis of meson exchange theory a "proton" charge radius r_{ch} of order m_Q^{-1}. This is, however, clearly the wrong answer: this "proton" will have a charge radius of order $(m_Q \alpha_s)^{-1}$ corresponding the the three particle Bohr radius of the UUD ground state.

This discrepancy is a variant of one resolved long ago by nuclear theorists for the deuteron: it is a consequence of "anomalous thresholds" [10,11]. The discrepancy (and the speculation that anomalous thresholds were its resolution) was noted in the context of heavy quarks in Ref. 12. The resolution is more subtle in the case of heavy quarks than in the case of the deuteron, however, since with confinement there are no actual anomalous thresholds (the deuteron can be dissociated into its constituents, but a hadron cannot be), but it has now been satisfactorily accomplished[13]. The essential point for us is that one can see explicitly in the dispersion relations for both normal bound states and confined ones that there are contributions to the form factor of a composite system arising from two intrinsically distinct physical mechanisms: structure associated with the spatial extension of the composite system (the anomalous threshold term) and structure associated with the current-constituent vertex function (the normal dispersion relation terms).

I should quickly add that the additional effect being discussed here is not associated with, for example, an NNV vertex arising from form factors for the strong emission of a vector meson V from the nucleon. There will also be such an effect related to compositeness, but it simply modifies the hadronic matrix element of the current-constituent vertex. The main effect is a *direct* one, best illustrated by the canonical example: a system with reduced mass μ and binding energy ϵ has an asymptotic wavefunction

$$\psi \sim \frac{1}{r} exp[-(2\mu\epsilon)^{1/2} r].$$

This leads to a form factor with a cut starting at $q^2 = 32\mu\epsilon$. Note that this anomalous threshold cut is not associated with any physical thresholds; moreover, it dominates the charge radius if ϵ is small. Another example is also useful: a system confined by harmonic forces has $\psi \sim exp[-\frac{1}{2}\alpha^2 r^2]$ and a form factor $F(\vec{q}^{\,2}) \sim exp[-q^2/16\alpha^2]$ which means that in this case the charge radius is being controlled by a singularity at infinity!

The Nucleon-Nucleon Problem

The extension of these considerations to "nucleon"-"nucleon" scattering in a heavy quark world appears to be straightforward. Conventional meson theory would say that the "nucleon"-"nucleon" cross section would correspond to a low energy effective potential with a range of order m_Q^{-1}. Since the UUD "nucleon" has a size given by its Bohr radius, and since quark exchange will occur via residual color Coulomb interactions with the same range (outside this range they are screened since the "nucleon" is color neutral), the actual effective potential will have a range of order $(m_Q \alpha_s)^{-1}$. Moreover, the strength of quark exchange dominates that of meson exchange by many powers of α_s. Thus in the limiting heavy quark world where $m_Q \to \infty$, the "nucleon"-"nucleon" interaction is controlled entirely by the composite nature of the "nucleons". What is more relevant for the extrapolation to the real world is that by understanding this limit we can see that quark exchange and meson exchange are (as they are in the case of the form factor) physically distinct sources of interactions. Moreover, one can see from the extrapolation of m_Q down to Λ_{QCD} that in the real world there is no reason to expect other than that these two contributions to NN scattering are of comparable importance.

Let me close this section with a speculation. Since NN scattering is related to $N\bar{N}$ scattering by crossing, and since both amplitudes can be calculated in the heavy quark world, it may be possible to identify a combination of "N""N" and "N""$\bar{N}$" amplitudes which isolate the quark exchange contribution to "N""N" scattering at all $m_Q > \Lambda_{QCD}$. In this case one could reasonably argue that the same quantities would constitute a measure of the quark exchange contributions to NN scattering in the real world.

Conclusions

The heavy quark limit shows that meson theory can fail totally, and that as $m_Q \to 0$ so that QCD becomes a one scale theory there is every reason to expect that the two time-ordered graphs of the old string theory become comparable ($V_{meson} \sim V_{quark\ exchange}$). I believe we will eventually appreciate that only Yukawa's *original* meson (whose mass avoids the single scale argument by chiral symmetry) will survive as a distinct contributor to interhadronic forces, while other mesons and quark exchange will be merged into a single comprehensive nuclear theory of the future.

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scattering while he was a visitor with the CEBAF Theory Group. Since giving this talk, I have also benefited greatly from the knowledge and comments of my colleagues in the CEBAF Theory Group (especially Franz Gross) who have been participating in our workshop on "Nuclear Physics in a Heavy Quark World".

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